43-Gbit/s-channel-based DWDM System Technologies for the Photonic Transport Network

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Abstract

This paper describes recent technical progress and the evolution of dense wavelength division multiplexing (DWDM) system technologies based on 43-Gbit/s channels for the optical transport network (OTN). We describe the new digital frame format "OTU3: Optical Channel Transport Unit 3", which was recently standardized in ITU-T as a novel network node interface of the OTN using 43-Gbit/s channels. The new standard enables the transparent accommodation of multi-tributary service signals such as SDH (synchronous digital hierarchy), ATM (asynchronous transfer mode), Ethernet, and Fiber Channel in large payloads, and enhances the WDM (wavelength division multiplexing) network management capability of the OTN with its overhead byte. It also introduces the forward error correction (FEC) code byte in its frame to ensure high-quality transmission at over 1 Tbit/s based on 43-Gbit/s channels. New transmission technologies have established stable 43-Gbit/s-channel long-haul WDM transmission across the OTN. They include a novel bandwidth-efficient RZ (return-to-zero) modulation format and a novel error-control scheme using optical spectral redundancy as well as several hybrid optical amplification technologies.

1. Introduction

The recent growth of Internet traffic has accelerated the demand for even higher capacities. 40-Gbit/s-channel systems based on full electrical time division multiplexing (ETDM) [1]-[3] have matured rapidly. ETDM provides economical optical transport interfaces through the use of advanced LSI technology, which is accelerating the research and development of high-capacity DWDM (dense wavelength division multiplexing) transport systems based on 40-Gbit/s channels, which are nowadays considered to be viable as next-generation systems throughout the world [1]-[14]. They offer high capacity with fewer channels, attain high spectral efficiency based on today's mature WDM multiplexers with 50–200-GHz spacing, and could provide economic trunk transport networks with a small footprint [15]. The 43-Gbit/s channel has been recently been accepted by ITU-T (International Telecommunication Union – Telecommunication Sector) as a prime candidate for the future optical transport network (OTN) based on WDM technologies that will support the next-generation data-centric network [16]. We conducted the first field transmission experiment in NTT's network to confirm the feasibility of a 40-Gbit/s-channel-based transport system in 1996 [4]. This field experiment accelerated the research and development of 40-Gbit/s system technologies in NTT, leading to the first feasibility demonstration of a full-ETDM regenerative repeater system [1], [2], the first WDM laboratory experiment [5], the first WDM field trial [8], the first terabit-per-second laboratory experiment using 43-Gbit/s ETDM channels with additional overhead with forward error correction (FEC) [10] corresponding to the proposal of OTU3 digital frame in ITU-T [19], and the first 1-Tbit/s WDM field trial based on OTU3 [12].

This paper describes recent technical challenges and the future evolution of DWDM transport system technologies using 43-Gbit/s channels for the OTN. In section 2, we describe the concept and impact of the new digital frame format of the 43-Gbit/s channel: the optical channel transport unit 3 (OTU3), which has been standardized in ITU-T to enhance the network management capability of the OTN. In sec-

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tion 3, we introduce the advantages and issues of an OTN based on 43-Gbit/s channels. Section 4 describes the concept and several attractive features of novel bandwidth-efficient return-to-zero (RZ) formats including carrier-suppressed RZ (CS-RZ) to enhance the transmission performance of long-haul 43-Gbit/s/channels. Section 5 introduces a new error control scheme using optical spectral redundancy to enhance the signal-to-noise ratio for further evolution of the OTN. We conclude with a short summary and mention the future evolution of the OTN based on 43-Gbit/s channels.

2. Network requirements for the OTN and its international standardization

Network traffic is now dominated by IP-based data traffic instead of telephone-based traffic. The growth of Internet traffic demands that the backbone network offers high quality and cost effectiveness, as well as high capacity. The OTN based on high-capacity WDM (Fig. 1) is very attractive for such a network. The tributary client signals of the OTN are not only conventional SDH/SONET signals but also several types of IP-based client signal, such as GbE, 10GbE, and IP over SDH/SONET. Therefore network operators require a new digital frame format to accommodate such new client signals. They also need several operation, administration, and maintenance (OAM) functions of the OTN to be embedded in the transported signal. For this purpose, the optical path layer for the OTN was proposed [17], [18] and the optical-channel transport unit (OTU) was standardized in ITU-T Recommendation G.709 [16]. The bit-rates for OTU are categorized into OTU1, OTU2, and OTU3. The OTU3 bit-rate class was proposed by NTT. The OTU3 frame enhances the network management capability for an OTN based on 43-Gbit/s channels with high capacity (over 1 Tbit/s) [19], [20]. Table 1 and Fig. 2 show the hierarchy of OTU and the digital frame structure of OTU3, respectively, as described in ITU-T Recommendation G.709. OTU3 is defined as a 43-Gbit/s channel with the following features:

- Client overhead transparency for multiple services
- Digital supervision for enhancing WDM network management
- Enhanced transmission quality using FEC

The OTU payload was designed to accommodate many types of client data signal without terminating the overhead byte of the client signal. This ensures transparent transmission of the client information signal together with the overhead signal used for client's network control across the backbone network, which is desirable for providing a client's virtual private network (VPN) across the OTN. The introduction of a structure for multiplexing ODUk-1 into ODUk is also described in G. 709 amendment (ODU: optical data unit). OTN multiplexing efficiently uses the wavelength resources, especially when the client has a lower bit-rate interface/equipment. The large capacity of the OTU3 payload is attractive not only as a bulk container but also as a multiplexed payload container because of its improvement in multiplexing gain.

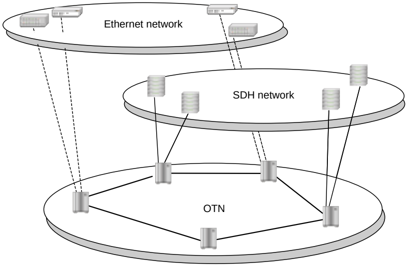

Fig. 1. Optical transport network (OTN).

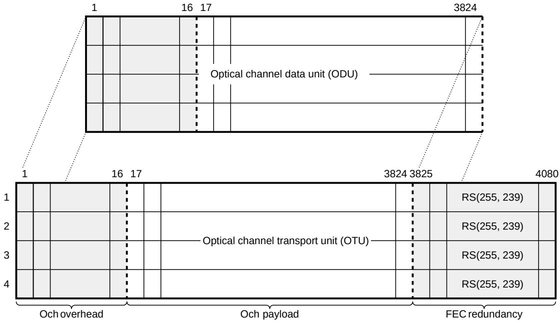

Fig. 2. Digital frame of optical channel transport unit.

Table 1. Hierarchy of OTU.

	Line rate (Gbit/s)	Frame period (μs)	Line rate increase
OTU 1	2.666057143	48.971	STM-16 × (255/238)
OTU 2	10.709225316	12.191	STM-64 × (255/237)
OTU 3	43.018413559	3.035	STM-256 × (255/236)

The OTU frame offers us overhead bytes of WDM network management for the network node interface, for the first time. Namely this format will be used all over the world as the Inter Domain Interface (IrDI) to link the networks of different telecom-carrier companies or sub-networks within a carrier's network. The overhead provides functions of frame synchronization, digital performance monitoring, data communication channel, automatic protection switching, and trail tracing. These overheads are also attractive for future OTN evolution into the multiprotocol lambda switching (MPλS) network, which will offer rapid, cost-effective provisioning.

Reed Solomon (RS) (255, 239) code is introduced as an out-of-band FEC code in the OTU frame at the expense of a 7% increase in line rate. The RS (255, 239) algorithm is widely used in today's submarine systems. The FEC code can improve the bit error rate (BER) from 10^{-4} to 10^{-15}, resulting in a coding gain of about 6 dB at BER of 10^{-12}, if the errors obey random (Poisson) statistics. The strong FEC capability increases the system margin to ensure several network evolution scenarios. The margin is effective for increasing the regenerative repeater span across several optical network elements such as optical cross connects (OXCs) and optical add/drop multiplexers (OADMs). It also allows more WDM channels for a given regenerative span and transmission performance. FEC is also helpful for digital performance monitoring. When bit errors occur in an optical channel, they are detected and corrected at the receiver side in the FEC decoder, without clients seeing any degradation. This ensures error-free transmission of the client signal, even if some bit errors occur in the OTN section. This feature lets network operators improve network operations based on early warning of forthcoming failures.

3. Advantages and enabling technologies of an OTN based on 40-Gbit/s channels

3.1 Advantages of 40-Gbit/s channels

An OTN based on 40-Gbit/s channels has several advantages for a data-centric high-capacity backbone network [15], [19], [20].

- Multi terabit-per-second capacity with high signal spectral efficiency
- Small footprint and low cost
- Large bulk payload for data-centric client signal

There are two standards for the 40-Gbit/s digital frame structure: OTU3 and STM-256 (STM: synchronous transport module). OTU3 is basically standardized for multi-channel systems, while STM-256 is for single-channel systems. It should be noted that OTU3 can be used in single-channel systems, while STM-256 may be used in multi-channel systems using the pre-OTN regime. Considering that recent systems require WDM upgrading, not only in point-to-point topology but also toward optical ring or mesh topology, OTU3 is suitable for today's network requirements in terms of transmission quality (by the use of out-of-band FEC*1) and management capability. Figure 3 shows the recent relationship between the signal spectrum efficiency and channel spacing with channel rate as a parameter. When the channel rate is increased from 2.4 to 40 Gbit/s, the modulation bandwidth of a 40-Gbit/s signal completely fills the available channel bandwidth of today's mature WDM filter with 50–200-GHz channel spacing. Therefore, the combination of today's mature DWDM system and 40-Gbit/s channels simply offers us high signal spectral efficiency up to 1 bit/s/Hz. Efficiencies of over 0.4 bit/s/Hz yield capacities beyond 1 Tbit/s within the typical bandwidth of 4 THz (30 nm) for optical fiber amplifier repeaters available in the C, L, and S bands. Thus multi-Tbit/s transmission is possible with a multi-band inline-repeater system, while 1 Tbit/s can be easily achieved with a simple single-band repeater system.

The small number of channels of the WDM system is also attractive because the network operation system has fewer objects (network elements) to supervise. This simplification also allows the network management capability to be enhanced. Such features also reduce the footprint of equipment in offices and network maintenance requirements.

3.2 Issues and enabling technologies

The most important issue in achieving a cost-effective OTN based on 40-Gbit/s channels is to overcome the transmission distance limitation due to imperfections in the optical fiber such as fiber nonlinear effects, group velocity dispersion (GVD), and polarization mode dispersion (PMD). The decrease in signal-to-noise ratio due to the increase in signal bandwidth requires an increase in the optical signal launched power. This will further increase the impact of fiber nonlinear effects. It is also very important in achieving uniform transmission performance over the entire fiber bandwidth (C, L, and S bands) given that

*1 out-of-band FEC: Out-of-band FEC is the FEC whose redundancy byte is defined independantly of the encoded signals mapped in the payload.

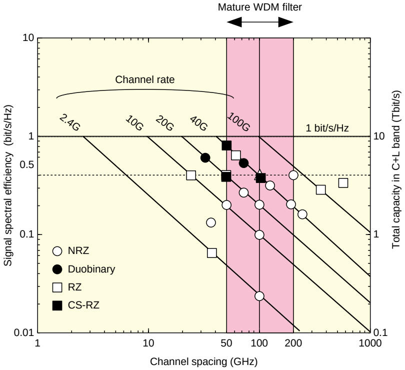

Fig. 3. Enhancement of spectral efficiency using 43-Gbit/s channel.

various types of fiber will exist; a variety of OTN upgrade scenarios should be supported. Nowadays, several digital and analog technologies have been tested to overcome these problems for 40-Gbit/s channel transmission, as shown by Table 2. For digital technologies, the RS(255, 239) FEC code in OTU3 is important for enhancing the performance regardless of the limiting factors. Another attractive digital error correction that has recently been proposed [21] offers further BER improvement without increasing the line rate, as described in Section 5. For analog technologies, three key technologies have been tested: the modulation and detection format [22], hybrid optical amplification using an erbium-doped fiber amplifier (EDFA) and a distributed Raman amplifier (DRA) [23], and dispersion compensation in terms of GVD and PMD including dispersion slope management [6]. Hybrid optical amplification is very attractive for reducing the impairment due to fiber nonlinearities, as well as enhancing the signal-to-noise ratio. However, it does not increase the robustness against the linear impairment caused by GVD and PMD. Guidelines and shut-down mechanisms to ensure safety for human eyes and network facilities are the key to actually deploying high-power distributed Raman amplifier systems [24]. In contrast to dispersion compensation and hybrid optical amplification, selecting the most appropriate modulation format in combination with FEC is very effective for increasing the robustness against all types of impairments. Here we focus on the impact of the modulation format and its combined effect with error correcting technologies on 40-Gbit/s WDM transmission performance.

4. Bandwidth-efficient RZ modulation format

4.1 Requirements

The requirements that the modulation format must satisfy are listed below for both single-channel and WDM applications.

- Compact modulation spectrum
- Simple configuration of transmitter and receiver
- High nonlinearity tolerance
- Simple dispersion characteristics in linear and nonlinear transmission

A compact modulation spectrum is desirable because this offers high signal spectrum efficiency in WDM systems and increases the GVD tolerance. High signal spectral efficiency of over 0.4 bit/s/Hz (or a spacing of less than 100 GHz) should be achieved in 40-Gbit/s-channel DWDM systems based on today's mature WDM filters [3], [15], which offer higher signal spectral efficiency than 50-GHz-spaced 10-Gbit/s-channel DWDM systems. High nonlinearity tolerance is also necessary for single- and multi-channel long-haul applications. Simple transmitter and receiver configurations are desirable for cost-effective transmitter and receiver blocks. Since the dispersion tolerance of a 40-Gbit/s channel is only 100 ps/nm, automatic dispersion compensation is strongly required. The simplest dispersion compensation approach is to set the total dispersion to zero. Therefore, the modulation format should be robust against fiber nonlinearity to offer us an optimized system parameter for operation in the zero total dis-

Table 2. Enabling technologies for 43-Gbit/s channel transmission.

Limiting factors \ Enabling technology	Analog			Digital
	Modulation format	Distributed amplification	Dispersion compensation	FEC
Signal-to-noise ratio	Yes	Yes	No	Yes
Linear				
• GVD	Yes	No	Yes	Yes
• PMD	Yes	No	Yes	Yes
Nonlinear				
• SPM	Yes	Yes	Yes	Yes
• XPM	Yes	Yes	Yes	Yes
• FWM	Yes	Yes	Yes	Yes

GVD: group velocity dispersion, PMD: polarization mode dispersion,
SPM: self phase modulation, XPM: cross phase modulation, FWM: four-wave mixing,
FEC: forward error correction.

persion region.

4.2 Proposed bandwidth-efficient RZ format

Our approach to such a modulation format is to reduce the bandwidth of the RZ format using phase reversal in the pulse generation and data encoding processes [22]. The bandwidth-efficient RZ format is very attractive for achieving stable long-haul DWDM transmission at channel rates of over 40 Gbit/s. It offers high-spectral efficiency while suppressing the effect of fiber nonlinearity, providing robustness against changes in GVD caused by fiber temperature fluctuation and network reconstruction, which are important benefits in terrestrial systems. Since the RZ format is robust against fiber nonlinearity, several RZ formats were proposed for transoceanic systems. Conventional RZ formats, however, require a modulation bandwidth of over 4B, as shown in Fig. 4(c) (where B is the line rate). This induces a large crosstalk penalty if we target spectral efficiencies of over 0.4 bit/s/Hz. Several approaches to reducing the modulation bandwidth of the RZ format apply periodic phase modulation in the pulse generation process. The carrier-suppressed RZ (CS-RZ) format [7], [25] reduces it to less than 3B by using alternate-bit-phase reversal in the pulse generation process, as shown in Fig. 4(b). This also enhances the tolerances to fiber nonlinearity.

The idea of the CS-RZ format is shown in Fig. 5. In the conventional RZ format, the electrical field of RZ

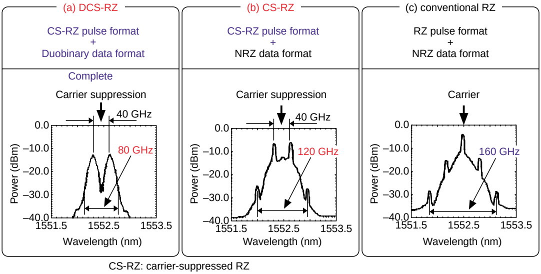

Fig. 4. Bandwidth reduction of RZ format.

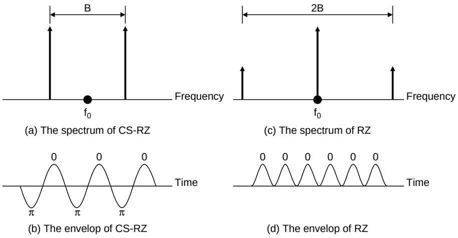

Fig. 5. Bandwidth reduction using two-mode beat pulse.

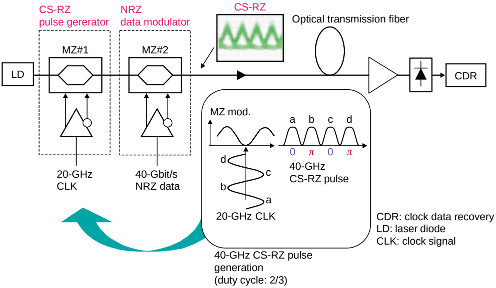

Fig. 6. Configuration of CS-RZ transmitter.

pulse train is expressed as formula (1), where the optical-pulse-repetition frequency B is equal to the line rate, $E_0/2$ is the amplitude, and f_0 is the optical carrier frequency.

$$E(t) = \frac{E_0}{2} \cdot \{1 + \cos(2\pi Bt)\} \cdot \exp(-j2\pi f_0 t). \qquad (1)$$

The envelop of the signal is sinusoidal with the frequency of B as shown in Fig. 5(d), and the Fourier spectrum consists of three mode-locked modes with the bandwidth over 2B as shown in Fig. 5(c).

In the CS-RZ format, on the other hand, the electrical field of CS-RZ pulse train is expressed as formula (2).

$$E(t) = E_0 \cdot \cos\left(\frac{2\pi Bt}{2}\right) \cdot \exp(-j2\pi f_0 t). \qquad (2)$$

The envelop is sinusoidal with the half frequency (B/2) of conventional RZ as shown in Fig. 5(b). Two beating modes are basically used in the Fourier spectrum and the mode spacing is exactly equal to the line rate as shown in Fig. 5(a). It should be noted the required bandwidth for CS-RZ pulse train is reduced to the half of conventional RZ thanks to the phase reversal in CS-RZ format. This two-mode-beat pulse train is modulated with the non-return-to-zero (NRZ) format to generate the proposed format. We called this format the "CS-RZ" format because of the spectral feature of carrier suppression in the modulation spectra.

Figure 6 shows the basic CS-RZ transmitter configuration and its operation. Two Mach-Zehnder (MZ) modulators are connected in series. One is used as an NRZ data modulator and the other as a two-mode beat pulse generator. We were the first to propose and demonstrate the field-deployable chirp-free CS-RZ transmitter based on a two-stage MZ modulator design that offers the several advances needed to achieve high-bit-rate data modulation at over 40 Gbit/s: stable polarization-maintaining interconnection between the pulse generator and the data modulator, compact integration, precise phase adjustment and stable synchronization between the pulse generation with an adjustable duty cycle and data modulation. As shown in Fig. 6, the MZ modulator is biased at the transmission null point and driven at a frequency of half the line rate. In the 40-Gbit/s CS-RZ transmitter, the required clock is 20 GHz. The frequency-doubling feature is very attractive because it reduces the operating frequency of the driving signal, which simplifies signal handling and relaxes the clock driver specification compared with the conventional RZ format. Due to the phase encoding characteristics of the MZ modulator, the generated clock pulse train is accompanied by alternate bit phase reversal, as shown in Fig. 6.

Figure 7 shows the advantage of CS-RZ format over the conventional NRZ and RZ formats. The transmission performance of the CS-RZ format surpassed those of the NRZ and RZ formats in a 360-km dispersion-managed fiber with 200-GHz-spacing WDM. In the case of the NRZ format, the self-phase modulation and signal-to-noise ratio strongly degrade the transmission performance. On the other

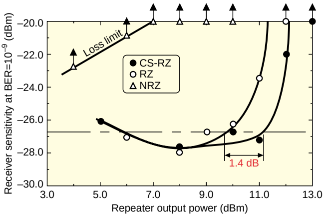

Fig. 7. Enhancement of SPM tolerance using CS-RZ.

hand, RZ and CS-RZ achieve stable transmission performance. The transmission performance of the CS-RZ format is more than 1 dB better than that of the RZ format. This enhancement of CS-RZ is further enhanced when the signal spectral efficiency is over 100 GHz.

Further RZ modulation bandwidth reduction, down to 2B, can be achieved with the duobinary CS-RZ (DCS-RZ) format [22], as shown in Fig. 4(a), which uses phase-reversal modulation in both the pulse generation and the data encoding processes based on the optical duobinary format; namely, the DCS-RZ format has alternate-mark-bit-phase reversal. Improvement in dispersion tolerance and DWDM spectral efficiency (up to 0.4 bit/s/Hz), and high fiber-nonlinearity tolerance have been reported for DCS-RZ.

4.3 Terabit-per-second capacity upgrade based on 43-Gbit/s channels using FEC

Figure 8 shows the experimental setup that first demonstrated the impact of the CS-RZ format and RS (255, 239) FEC code on an OTN that uses 43-Gbit/s channels in a 1.2-Tbit/s (30 × 43 Gbit/s) WDM experiment [10]. Two types of 43-Gbit/s test signal with and without FEC were used to check the FEC performance.

30-channel 43-Gbit/s CS-RZ signal transmission was established over a 376-km dispersion-flattened dispersion-managed line with total repeater output power of over +20 dBm (+5 dBm/channel average).

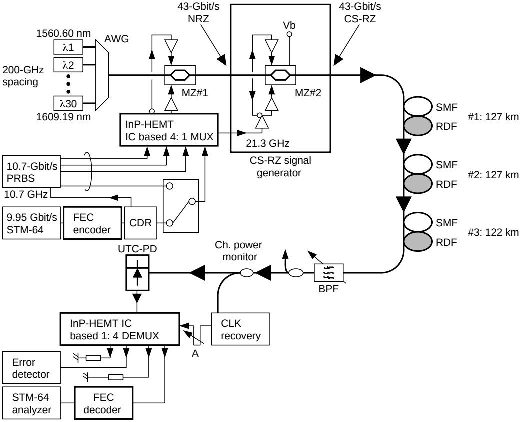

Fig. 8. Experimental setup for 1.2-Tbit/s (30 × 43 Gbit/s) WDM transmission.

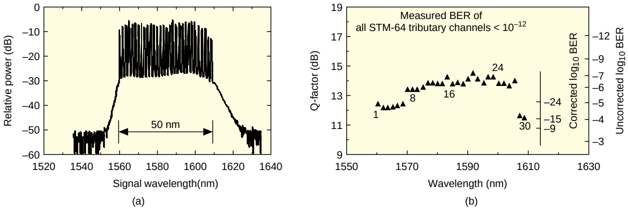

Fig. 9. Terabit/s WDM upgrade using FEC based on 43-Gbit/s optical channel.

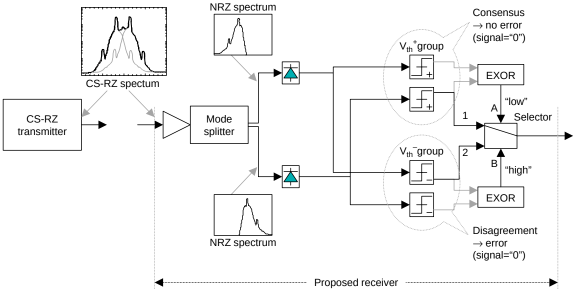

Fig. 10. Receiver configuration for proposed error-control.

Figure 9 shows the 1.2-Tbit/s WDM transmission performance. The WDM spectra after transmission are shown in Fig. 9(a). There is no four wave mixing crosstalk component in the WDM spectra. Figure 9(b) shows the BER improvement achieved using FEC. All the 43-Gbit/s channels were successfully transmitted with error free operation by employing FEC for all channels.

The use of 43-Gbit/s channels with FEC in a terabit-per-second WDM system allows the span loss to be as high as 30 dB, even if the channel power is 6 dB less than the level used in the 8 × 40 Gbit/s channel WDM experiment without FEC, as described in ref. [7]. The STM-64 client channels were multiplexed and transmitted with bit error rates better than 10^{-15} while keeping client overhead transparency.

5. Novel high-gain error control using optical spectrum redundancy

5.1 Spectrum redundancy in CS-RZ format

The CS-RZ format is characterized by its dual-mode spectrum redundancy. The CS-RZ pulses are generated as the beat between two different longitudinal modes, and each mode is intensity-modulated with NRZ data [7]. This view of the CS-RZ spectrum suggests that the frequency components can be separated by optical filtering; each separated signal should have the NRZ format, as experimentally verified [27]. Figure 10 shows a general diagram of our novel error control technique, where two optical-electrical (O/E) conversion blocks are employed [21]. After dual O/E conversion, we employ special digital processing to achieve the error control (details are described in the following sub-sections). It should be noted that the two frequency components of the CS-RZ signal experience different noise environments created within the optical amplifiers in the transmission line because the components have different central frequencies and spectra. We assume that amplified spontaneous emission (ASE) from optical amplifiers is the dominant noise source in the systems. The ASE noise on each component is generated by a different energy state transition of the Er^{3+} electrons in the optical fiber amplifiers. Therefore, mode-splitting yields two NRZ signal encoded by the same logic, each of which is accompanied by independent noise.

5.2 Novel error control principle

Error-control circuits are used to implement two basic digital operations: error detection and data recovery.

To detect errors, the proposed scheme subjects the split signal to "consensus" logic. Chromatic dispersion compensation is assumed, so the delay difference between the two NRZ signals should be offset. In the receiver, the transmitted signal is split into two by an optical mode-splitting filter. CS-RZ already offers 100% redundancy, and we use this spectral redundancy to achieve error control. After dual (or diverse) optical reception, each split baseband signal is divided into two more branches. Each divided signal enters a decision circuit, each of which has one of two different threshold levels: a high decision threshold V_{th}^{+} or low decision threshold V_{th}^{-}. Hence, there are four decision circuits in total and we form them into two groups according to the threshold: the V_{th}^{+} group and V_{th}^{-} group. The outputs of the groups represent the decision-answers of the same logic with independent noise. Within each group, the "consensus" or "disagreement" is tested. If the result is "consensus", the group will have the correct decision, so the threshold is likely to provide no error. If the result is "disagreement", the group contains a wrong decision, so the threshold is erroneous. This forms a bit-by-bit error detection mechanism that dispenses with the use of frames, codes, and all complex calculations. The "consensus" test is achieved simply by using two Exclusive-OR (EXOR) circuits.

To recover data, the scheme employs bit-by-bit selection of the decision threshold voltage, as shown in Fig. 11. For signal "1" (upper figure), the decision with a low threshold voltage provides better performance than the conventional optimum threshold, while for signal "0" (lower figure), the decision with a high threshold voltage provides better performance. As illustrated in Fig. 11, if the V_{th}^{+} group provides no error and the V_{th}^{-} group does provide errors, the signal is very likely to be binary encoded by "0". In this case, V_{th}^{+} is selected in the bit-period. The selector logic is as follows. Assume it has two main-signal ports 1 and 2, and two control ports A and B, as shown in Fig. 10. The main-signal port 1 is associated with control port A, while 2 is associated with B. If A is "low" and B "high", the selector selects port 1. If A is "high" and B "low", the selector selects port 2. The selector holds the same state as the previous bit when the two EXOR circuits generate double "low" (consensus in both groups) or double "high" (disagreement in both groups). As the bit-by-bit selector, we can use a high-speed 2:1 multiplexing circuit.

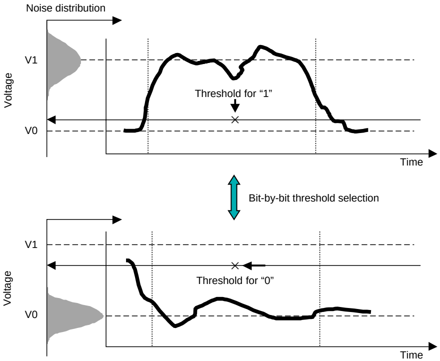

Fig. 11. Bit-by-bit threshold selection improves BER.

5.3 Performance estimation

The probability that errors will propagate to downstream circuits is determined by two factors: double errors in each group, and double disagreement among answers in both groups. The former factor can be expressed as the product of the probabilities of erroneous decisions regarding the same signal with independent noise. When considering the upper port of the selector in Fig. 10, the probability of double errors is given by $1/2*P^2(1,V_{th}^+)+1/2*P^2(0,V_{th}^+)$, where $P(x,V_{th}^y)$ means the error probability of signal "x"=(0,1) with threshold "y"=(+,–) decision. In the above expression, the mark ratio is assumed to be 1/2. Similarly, the probability of double errors in the lower port of the selector is given by $1/2*P^2(0,V_{th}^-)+1/2*P^2(1,V_{th}^-)$. When considering the double disagreement factor of error propagation, it should be noted that we use electronic "copies" of the same signals with independent noise (the total number of signals is four). Therefore, the upper decision circuit in the V_{th}^+ group and the upper decision circuit in the V_{th}^- group experience exactly the same noise. We assume that the dominant errors are due to ASE noise from optical amplifiers because the thermal noise and shot noise in the receiver are negligible. The probability of double disagreement is estimated as the lower of two probabilities: $\min\{P(0,V_{th}^+), P(0,V_{th}^-)\}=P(0,V_{th}^+)$ for "0" and $\min\{P(1,V_{th}^+), P(1,V_{th}^-)\}=P(1,V_{th}^-)$ for "1". In the equilibrium condition, when errors exist, the probability of the selector selecting the upper or lower port can be assumed to be approximately 1/2. Therefore, the probability of an error propagating through the receiver is given by

$$P_e = \frac{1}{4}P^2(1,V_{th}^+) + \frac{1}{4}P^2(0,V_{th}^-) + \frac{1}{2}P(0,V_{th}^+) + \frac{1}{2}P(1,V_{th}^-). \qquad (3)$$

In the above expression, $P^2(0,V_{th}^+)$ and $P^2(1,V_{th}^-)$ are neglected. Here, for simplicity, we assume that the noise in the system is additive white Gaussian noise (AWGN), where "0" and "1" have the same amount of standard deviation due to noise, around each average. It is well known that AWGN is not accurate in optical amplified systems, but this simplified model can provide a good understanding of the fundamental features of this new scheme. We use the Q factor of the ordinary AWGN model. Although it usually includes a threshold parameter, we place the threshold parameter outside the Q factor in the following expression assuming $Q=I/(2\sigma)$, where I is the signal voltage for "1" and σ is the standard deviation. The average voltage for signal "0" is assumed to be 0 for simplicity. The error probability is given by

$$P_e = \frac{1}{8}Erfc^2\{\frac{2(1-x)Q}{\sqrt{2}}\} + \frac{1}{2}Erfc\{\frac{2xQ}{\sqrt{2}}\}, \qquad (4)$$

where x is the ratio of decision threshold voltage V_{th}^+ and signal "1" voltage. Here, Erfc(u) is the well-known complementary error function defined as

$$Erfc(u) = \frac{2}{\pi}\int_u^{\infty}\exp\{-u^2\}du. \qquad (5)$$

The optimum thresholds for this receiver are calculated as x=0.6 and 0.4 for V_{th}^+ and V_{th}^-, respectively. The error control performance should be the relationship between raw (input) and controlled (output) BER calculated from (4), especially if the raw BER curve is not as steep as in the theoretical error-function.

5.4 Experimental verification

The proposed error controlling receiver was built and tested with the addition of 7% FEC code, at the data rate of 10.7 Gbit/s. In this experiment, we used the 10.7-Gbit/s RS(255, 239) standard FEC frame for data transmission and 42.7-GHz CS-RZ pulses for dual mode generation. There will no difficulty in supporting 43-Gbit/s data transmission because 43-Gbit/s electronic devices are already available. Experimental results are shown in Fig. 12. The open circles plot the raw BER without any error control by the conventional receiver and with FEC decoder inactive. The green circles represent the results with the proposed receiver without FEC decoding. The thick black line represents a theoretical estimation calculated from the relationship between raw BER and output BER obtained from equation (2). The raw BER of 10^{-6} was improved to 5×10^{-10}, which is slightly better than the above estimation. This is due to the simple approximation that noises are AWGN. In this experiment, the gain was 3 dB at the BER of 10^{-12}. The leftmost plots represent the performance of the proposed receiver together with RS(255, 239). We achieved error free operation ($<10^{-12}$) at the received optical power of –38.5 dBm. Total gain with the proposed scheme and 7% FEC was 9 dB. The important point to note is that the gain of our technique follows the simple sum-rule, e.g, FEC gain (6 dB) plus pulse error-control gain (3 dB). This is due to the characteristics of the receiver: it proceeds on a bit-by-bit basis and is thus independent of error statistics. The usual FEC concatenation approaches do not offer a sum-rule for coding gain because their performance

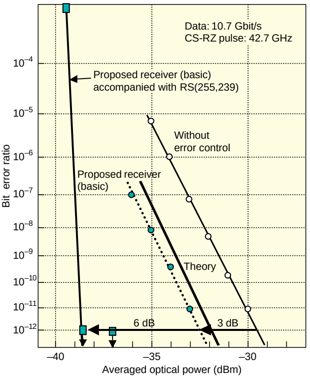

Fig. 12. BER performance of proposed error-control scheme.

depends on error statistics (errors after the first decoding show strong burst-error characteristics). This independence of error statistics of the proposed receiver enhances its tolerance against PMD, whose error statistics have burst-error characteristics [28].

6. Conclusion

This paper described recent progress in the optical transport network based on 43-Gbit/s channels. A novel digital frame format for the optical transport unit (OTU) has been standardized to ensure a highly reliable and cost-effective optical transport network (OTN) that can transport today's data-oriented multi-client services transparently. The OTU frame offers an overhead byte that is dedicated to WDM network operation and the transmission performance improvement offered by RS(255, 239) forward error correction code at the expense of only a 7% increase in line rate. Novel bandwidth-efficient formats, including CS-RZ, are very effective for achieving long-haul transport systems with high spectral efficiency of over 0.4 bit/s/Hz. The ITU-T standard FEC not only enhances the transmission performance of 43-Gbit/s channels, but also allows bit-error-rate performance monitoring while keeping transparent client signal transmission in the OTN. A novel error correction scheme using optical spectral redundancy has great potential to increase the system margin by 9 dB in combination with the standard RS(255, 239) without any additional line rate increase. These technologies ensure the practicality and evolution of the OTN based on 43-Gbit/s channel in combination with several hybrid optical amplification technologies including distributed Raman and erbium-dopod fiber amplifiers.

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